Summary of the Theory Part of the International Conference on Elastic and Diffractive Scattering - "Frontiers in Strong Interactions" (VIth Blois Workshop), Chateau de Blois, France, June 20 -24, 1995

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Abstract

The theory part of the conference is summarized with certain emphasis on the results concerning the pomeron in soft and hard processes.

When summarizing the content of the meeting which embraced the very wide spectrum of subjects ranging from the classical dispersion relation analysis of forward scattering to the theory of hard processes based on perturbative QCD it is useful to find some "common denominator" of as many presentations as possible. I believe that a possible choice in this case might be the pomeron structure in soft and hard processes.

Substantial part of this conference has been as usual devoted to the analysis of the forward scattering amplitude parameters (i.e. of $\sigma_{tot}(s)$ and ρ) in a model independent way assuming only dispersion relations and various forms of the asymptotic parametrisations of the cross-sections which respected the Froissart-Martin bound and other asymptotic theorems. The theoretical discussion of the forward scattering amplitude has been presented in [1, 2, 3, 4, 5, 6, 7, 8]. The data seem to support the dominance of the crossing-even amplitude and there is little evidence for a significant odderon contribution in forward and near forward scattering. The real part just reflects (through the dispersion relations) the increase of the total cross-sections with increasing energy.

We have had numerous contributions to this conference discussing various aspects of the pomeron physics ranging from the pure phenomenology to the discussion of formal problems of the pomeron singularity in perturbative QCD.

The term "pomeron" corresponds to the mechanism of diffractive scattering at high energy. It is relevant for the description of several phenomena and quantities like the total cross-sections $\sigma_{tot}(s)$ and their energy dependence, the real part of the scattering ampltude, the variation with energy of the differential elastic cross-section $d\sigma/dt$, behaviour of the diffractive cross-section $d\sigma/dtdM^2$, behaviour of the deep-inelastic scattering structure function $F_2(x,Q^2)$ at low x, behaviour of the diffractive structure function etc.

The simplest yet presumably very incomplete description of the pomeron is within the Regge pole model. In this model one assumes that a pomeron is described by a Regge pole with the trajectory $\alpha_P(t) = \alpha_P(0) + \alpha' t$. The scattering amplitude corresponding to the pomeron exchange is given by the following formula:

$$A(s,t) = -g(t)\frac{exp(-i\frac{\pi}{2}\alpha_P(t))}{sin(\frac{\pi}{2}\alpha_P(t))}s^{\alpha_P(t)} \tag{1}$$

where the function $g(t)$ describes the pomeron coupling. Using the optical theorem one gets the following high energy behaviour of the total cross-sections:

$$\sigma_{tot}(s) \sim \frac{ImA(s,0)}{s} = g(0)s^{\alpha_P(0)-1} \tag{2}$$

One also gets:

$$\rho = \frac{ReA(s,0)}{ImA(s,0)} = ctg(\frac{\pi}{2}\alpha_P(0)) \tag{3}$$

with corrections from low lying Regge trajectories which vanish at high energies approximately as $s^{-1/2}$. It follows from (2) that the Regge-pole model of a pomeron can describe the increase of the total cross-sections with energy assuming $\alpha_P(0) > 1$ but this parametrization will eventually violate the Froissart-Martin bound.

Phenomenological description of σ_{tot} and of $d\sigma/dt$ proceeds in general along the following two lines:

1. One introduces the "effective" (soft) pomeron with relatively low value of its intercept ($\alpha_P(0) \approx 1.08$ [9]) which can very well describe the high energy behaviour of all hadronic and photoproduction cross-sections (with possible exception of the one CDF point). In phenomenological analysis one also adds the reggeon contribution which gives the term $\sigma_{tot}^R \sim s^{\alpha_R(0)-1}$ with $\alpha_R(0) \approx 0.5$.
   The power-like increase of the total cross-section has to be, of course, slowed down at asymptotic energies but those corrections are presumably still relatively unimportant at presently available energies. It has however been observed [10] that the soft pomeron can violate unitarity for central pp partial wave already for $\sqrt{s} > 2.5TeV$.

2. One considers from the very beginning the unitarized amplitude using the eikonal model [10, 11, 12]. In this model the partial wave amplitude $f(s,b)$ has the form

$$f(s,b) = \frac{1}{2i}[exp(-2\Omega(b,s)) - 1] \tag{4}$$

$$\Omega(s,b) = h(b,s)s^{\Delta}\frac{exp(-i\frac{\pi}{2}\Delta)}{cos(\frac{\pi}{2}\Delta)} \tag{5}$$

   where $\Delta > 0$ and $h(b,s)$ is the slowly varying function of s. The variable b denotes the impact parameter. The eikonal function can be viewed upon as originating from the "bare" pomeron with its intercept $\alpha_P(0) = 1 + \Delta$ being above unity. The eikonal models with $\Omega(s,b) \sim s^{\Delta}(\Delta > 0)$ lead to the scattering on the expanding (black) disk at asymptotic energies. The radius of the disk grows logarithmically with increasing energy (i.e. $R(s) \sim ln(s)$). This leads to the saturation of the Froissart-Martin bound at asymptotic energies and to the deviation of the shape of the diffractive peak from the simple exponential. Inelastic diffractive scattering becomes peripheral at asymptotic energies [10]. The recent fits presented in this conference [10, 12] give rather large values of Δ ($\Delta \approx 0.3$ or so). This parameter had a relatively small value $\Delta \approx 0.08$) in the original eikonal model of Bourely, Soffer and Wu formulated more then 20 years ago (see [11] and references therein). Other aspects of the eikonal model (called also the Chou-Yang model) have been presented in [13, 14].

The Regge phenomenology may also be applicable in the analysis of the deep inelastic scattering in the limit when the Bjorken variable x is small. The inelastic lepton scattering (i.e. the reaction $l(p_l) + p(p) \rightarrow l'(p_l') + anything$) is related through the one photon exchange approximation to the forward virtual Compton scattering $\gamma^*(Q^2) + p(p) \rightarrow \gamma^*(Q^2) + p(p)$ where $Q^2 = -q^2$, $q = p_l - p_l'$ and $x = Q^2/2pq$. The measured structure functions $F_2(x, Q^2)$ and $F_L(x, Q^2)$ are directly related to the total (virtual) photoproduction cross-sections σ_T and σ_L corresponding to transversely and longitudinally polarized photons:

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2\alpha}(\sigma_T + \sigma_L) \tag{6}$$

$$F_L(x, Q^2) = \frac{Q^2}{4\pi^2\alpha}\sigma_L \tag{7}$$

Assuming the conventional Regge pole parametrisation for $\sigma_{T,L}$

$$\sigma_{T,L} = \frac{4\pi^2\alpha}{Q^2}\sum(\frac{2pq}{Q^2})^{\alpha_i(0)-1}C^i_{T,L}(Q^2) \tag{8}$$

one gets the following small x behaviour for the structure functions:

$$F_{2,L} = \sum(x)^{1-\alpha_i(0)}C^i_{T,L}(Q^2) \tag{9}$$

where the sum in (8,9) extends over the pomeron and the reggeon contributions. The experimental results from HERA show that the structure function $F_2(x, Q^2)$ for moderate and large Q^2 values ($Q^2 > 1.5\ GeV^2$ or so) grows more rapidly then expected on the basis of the straightforward extension of the Regge pole parametrization with the relatively small intercept of the effective pomeron ($\alpha_P(0) \approx 1.08$) [16].

Very steep behaviour of parton distributions and of structure function $F_2(x, Q^2)$ has been predicted long time ago within the perturbative QCD and several talks in this conference were devoted to the discussion of the small x physics in perturbative QCD [9, 17, 18, 19, 20, 21, 22, 23, 24] (see also [38, 39, 40, 41]).

The relevant framework for discussing the small x limit of parton distributions is the leading $\log 1/x$ (LL$1/x$) approximation which corresponds to the sum of those terms in the perturbative expansion where the powers of α_s are accompanied by the leading powers of $\ln(1/x)$. At small x the dominant role is played by the gluons and the quark (antiquark) distributions as well as the deep inelastic structure functions $F_{2,L}(x, Q^2)$ are also driven by the gluons through the $g \rightarrow q\bar{q}$ transitions.

The basic quantity at small x is the unintegrated gluon distribution $h(x, k^2)$ which satisfies the following equation:

$$-x\frac{\partial h(x, k^2)}{\partial x} = \bar{\alpha}_s \int \frac{d^2q}{\pi q^2}[h(x, (\hat{q} + \hat{k})^2) - h(x, q^2)\Theta(k^2 - q^2)] \tag{10}$$

where $\bar{\alpha}_s = 3\alpha_s/\pi$. This equation is the celebrated Balitzkij, Fadin, Kuraev, Lipatov (BFKL) equation (see [17] and references therein) which corresponds to the sum of ladder diagrams with gluon emissions. The second term at the right hand side of the eq.(10) describes the virtual corrections. The longitudinal momenta are strongly ordered along the chain yet the transverse momenta are not ordered. The two-dimensional vector $\hat{k}$

describes the transverse momentum of the gluon while the vector $\hat{q}$ is the transverse momentum of the produced gluon "jet" at the last rung of the chain. The familiar (scale dependent) gluon distribution $g(x, Q^2)$ is related in the following way to the unintegrated distribution $h(x, k^2)$

$$xg(x, Q^2) = \int^{Q^2} dk^2 h(x, k^2) \tag{11}$$

After resumming the "unresolvable" real emission ($q^2 < \mu^2$) and virtual corrections one can rearrange the BFKL equation into the following form:

$$h(x, k^2) = h^0(x, k^2) + \bar{\alpha}_s \int_x^1 \frac{dz}{z} z^{\omega(k^2,\mu^2)} \int \frac{d^2q}{\pi q^2} h(\frac{x}{z}, (\hat{q} + \hat{k})^2) \tag{12}$$

where

$$\omega(k^2, \mu^2) = \bar{\alpha}_s ln(\frac{k^2}{\mu^2}) \tag{13}$$

The equation (12) sums now only the real resolvable radiation. The quantity $\omega(k^2, \mu^2)$ is directly related to the gluon Regge trajectory $\alpha_g(k^2, \mu^2)$

$$\omega(k^2, \mu^2) = 2(1 - \alpha_g(k^2, \mu^2)) \tag{14}$$

The equation (12) corresponds to the ladder diagrams with the reggeized gluon exchange along the ladder. One can also interpret the damping factor $z^{\omega(k^2,\mu^2)}$ which correspond to the reggeized gluon exchange as the "non-Sudakov form-factor" Δ_{NS}

$$\Delta_{NS} = z^{\omega(k^2,\mu^2)} = exp\left(-\bar{\alpha}_s \int_z^1 \frac{dz'}{z'} \int_{\mu^2}^{k^2} \frac{dk'^2}{k'^2}\right) \tag{15}$$

The asymptotic solution of the BFKL equation in the small x limit has the following form:

$$k^2 h(x, k^2) = C \frac{(\frac{k^2}{k_0^2})^{1/2}}{ln^{1/2}(1/x)} x^{-\lambda} exp\left(-\frac{ln^2(\frac{k^2}{k_0^2})}{2\lambda'' ln(1/x)}\right) \tag{16}$$

where

$$\lambda = \bar{\alpha}_s 4ln2 \tag{17}$$

and $\lambda'' = 28\bar{\alpha}_s\zeta(3)$ with the Riemann zeta function $\zeta(3) \approx 1.202$. The solution of the BFKL equation exhibits very strong increase with decreasing x when compared with the increase implied by the "soft" Pomeron since $\lambda >> 0.08$ for reasonable choice of the coupling $\bar{\alpha}_s$. The pomeron which is connected with the solution of the BFKL equation is usually referred to as the "hard" pomeron. It is expected to control the small x behaviour of (semi)hard processes.

The small x increase is correlated with the increase in k^2 and with the diffusion pattern of the solution of the BFKL equation. This is closely related to absence of transverse momentum ordering along the gluon chain and has several implications for the structure of the final state in deep inelastic scattering. There are several measurements which are aimed at revealing this mutual relationship between small x increase and the increase of transverse momentum. They are (for instance) measurements of energetic jets in deep inelastic scattering, measurements of the energy flow in the central region, measurements of azimuthal decorrelation of dijets etc. Several new experimental results concerning the study of the deep inelastic final state from the point of view of revealing the BFKL signals

have been reported in this conference [16, 25].

In the impact parameter representation the BFKL equation offers an interesting interpretation in terms of the colour dipoles and this approach has been summarized in the talk by Kolya Nikolaev [17]. Possible generalization of the BFKL formalism which includes energy momentum conservation constraint and the coherence effects was discussed by Gosta Gustafson [18].

Observable quantities at small x are calculated in terms of the solution of the BFKL equation using the k_t factorization theorem. The deep inelastic lepton hadron scattering is dominated at small x by the gluon-photon fusion and the k_t factorization formula for the structure functions $F_{2,L}(x,Q^2)$ then reads::

$$F_{2,L}(x,Q^2) = \int_x^1 \frac{dz}{z} \int dk^2 \hat{F}^0_{2,L}(\frac{x}{z},k^2,Q^2) h(k^2,z) \tag{18}$$

In this equation the functions $\hat{F}^0_{2,L}(\frac{x}{z},k^2,Q^2)$ are the structure functions of the off-shell gluon of virtuality k^2 and correspond to the quark box contribution to the gluon-photon fusion process. The unintegrated gluon distribution $h(k^2,z)$ is the solution of the BFKL equation. The small x behaviour of $F_{2,L}(x,Q^2)$ reflects the small z behaviour of $h(k^2,z)$ i.e. the structure functions at small x are driven by the gluon.

The leading twist part of the k_t factorisation formula can be rewritten in a collinear factorization form. The leading small x effects are then automatically resummed in the corresponding anomalous dimensions (or splitting functions) and in the coefficient functions. They can also affect the (nonperturbative) starting distributions. In this way one can systematically include the leading $\ln(1/x)$ effects within conventional formalism based on the Altarelli-Parisi evolution equations for parton densities and collinear factorization formulas for calculating the observable quantities. All these (and related) problems have been nicely summarized in the review talk given by Marcello Ciafaloni [19].

The possible role of the leading $\log 1/x$ resummation which go beyond the standard leading (or next-to-leading $\log(Q^2)$) QCD analysis is still not very well understood. In particular one can get equally good description of HERA data on $F_2(x,Q^2)$ using the QCD evolution formalism without those small x "corrections", provided that the starting parton distributions are changed appropriately. The structure function $F_2(x,Q^2)$ is therefore not the best "discriminator" of the BFKL small x effects and it is the dedicated study of final states in deep inelastic scattering (along the lines described above) which may prove to be a very useful tool for this purpose. The HERA data have nevertheless put important constraints on the small x behaviour of deep inelastic scattering which should have implications also in the kinematical range beyond that which is currently accessible. Possible implications of the QCD expectations for the small x behaviour of deep inelastic scattering for the estimate of ultra -high energy neutrino cross sections has been presented by Ina Sarcevic [26].

Several new interesting results have been reported which concern the formal studies of the high energy (or small x) limit in QCD beyond the leading logarithmic approximation [21, 22, 23, 24]. Important theoretical tool in this case is the effective field theory where the basic objects are the reggeized gluons and the effective action of this effective field theory obeys conformal invariance [21]. Theoretical analysis simplifies in the large N_c

limit and the theory resembles then the Ising model. One can discuss both the pomeron which appears as the bound state of two (reggeized) gluons, the odderon (i.e. the bound state of three reggeized gluons) as well as bound states of many reggeized gluons.

The next-to-leading $\ln(1/x)$ corrections can be present in all relevant quantities i.e. in the particle-particle-reggeon vertex, the reggeon-reggeon-particle vertex and in the gluon Regge trajectory. (The reggeon here corresponds to the reggeized gluon). Besides that one has also to include additional region of phase-space which goes beyond strong ordering of longitudinal momenta. The next-to-leading corrections to the gluon trajectory have been presented at this conference by Victor Fadin [23] and the results concerning those corrections to the BFKL kernel were reported by Alan White [24].

A large portion of the conference has been devoted to discussion of the deep inelastic diffraction [9, 17, 27, 29, 30, 31, 32] with the basic theoretical issues of diffraction summarized in the review talk given by Alosha Kaidalov [27]. It should also be reminded that the ideas concerning possible partonic content of the pomeron were for the first time reported by Ingelman and Schlein exactly ten years ago at the first Blois Conference in 1985.

The deep inelastic diffraction is a process:

$$l(p_l) + p(p) \rightarrow l'(p_l') + X + p'(p') \tag{19}$$

where there is a large rapidity gap between the recoil proton (or excited proton) and the hadronic system X. To be precise the process (19) reflects the diffractive disssociation of the virtual photon. Diffractive dissociation is described by the following kinematical variables:

$$\beta = \frac{Q^2}{2(p-p')q} \tag{20}$$

$$x_P = \frac{x}{\beta} \tag{21}$$

$$t = (p-p')^2. \tag{22}$$

Assuming that the diffraction dissociation is dominated by the pomeron exchange and that the pomeron is described by a Regge pole one gets the following factorizable expression for the diffractive structure function:

$$\frac{\partial F_2^{diff}}{\partial x_P \partial t} = f(x_P,t) F_2^P(\beta, Q^2, t) \tag{23}$$

where the "flux factor" $f(x_P,t)$ is given by the following formula :

$$f(x_P,t) = N\frac{B^2(t)}{16\pi} x_P^{1-2\alpha_P(t)} \tag{24}$$

with $B(t)$ describing the pomeron coupling to a proton and N being the normalisation factor. The function $F_2^P(\beta, Q^2, t)$ is the pomeron structure function which in the (QCD improved) parton model is related in a standard way to the quark and antiquark distribution functions in a pomeron.

$$F_2^P(\beta, Q^2, t) = \beta \sum e_i^2 [q_i^P(\beta, Q^2, t) + \bar{q}_i^P(\beta, Q^2, t)] \tag{25}$$

with $q_i^P(\beta, Q^2, t) = \bar{q}_i^P(\beta, Q^2, t)$. The variable β which is the Bjorken scaling variable appropriate for deep inelastic lepton-pomeron "scattering" has now a meaning of the momentum fraction of the pomeron carried by the probed quark (antiquark). The parton distributtions in a pomeron are assummed to obey the standard Altarelli-Parisi evolution equations:

$$Q^2 \frac{\partial q^P}{\partial Q^2} = P_{qq} \otimes q^P + P_{qg} \otimes g^P \tag{26}$$

with similar equation for the gluon distribution in a Pomeron. The first term in the right hand side of the eq. (26) becomes negative at large β while the second term stays always positive and is ussually very small at large β unless the gluon distributions are large and have a hard spectrum. The data suggest that the slope of F_2^P as the function of Q^2 does not change sign even at relatively large values of β that favours the hard gluon spectrum in a pomeron [27, 31, 32]. This should be contrasted with the behaviour of the structure function of the proton which , at large x, decreases with increasing Q^2. The data on inclusive diffractive production do also favour the soft pomeron with relatively low intercept. The diffractive production of vector mesons does seem to require "hard" pomeron contribution [9, 34, 33]. It has also be pointed out that he factorization property (23) may not hold in models based entirely on perturbative QCD when the pomeron is represented by the BFKL ladder [17, 29, 35].

The phenomenological as well as purely theoretical study summarized above indicate that we may have two pomeron contributions: the "soft" pomeron which is relevant for describing the soft processes and the "hard" one which shows-up at the processes characterized by a hard scale. This simple additive picture has however been questioned in some of the contributions to this conference [36].

Several contributions have been devoted to the spin effects in high energy scattering [42, 43, 44, 47, 45] and in particular to the disscussion of the polarized structure functions. The present theoretical situation in this field has been summarized by Stefano Forte [43].

The first moment of the (polarized) structure function $g_1(x, Q^2)$ is directly related to the matrix elementa of the axial current(s). For the isotriplet structure function one gets the Bjorken sum rule:

$$\int_0^1 dx (g_1^p(x, Q^2) - g_1^n(x, Q^2)) = \frac{1}{6} g_A C^{NS}(Q^2) \tag{27}$$

where

$$C^{NS}(Q^2) = 1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58 (\frac{\alpha_s(Q^2)}{\pi})^2 - 20.22 (\frac{\alpha_s(Q^2)}{\pi})^3 + ... \tag{28}$$

Analysis of the Bjorken sum rule can give an (independent) determination of α_s and the result of this analysis is:

$$\Lambda_{n_f=3}^{\bar{M}\bar{S}} = 383_{-116}^{+126} MeV \tag{29}$$

$$\alpha_s(M_Z^2) = 0.118 \pm 0.007 \tag{30}$$

The sum rules for the singlet structure function are sensitive through the axial anomaly on the polarized gluon distribution ΔG in a proton.

At small x the QCD corrections can be very important and can change the Regge pole like behaviour. The canonical Regge pole expectations is that the polarized structure function g_1 should have the power-like behaviour:

$$g_1(x, Q^2) \sim x^{-\alpha_A(0)} \tag{31}$$

where $\alpha_A(0)$ is the intercept of the Regge trajectory corresponding to axial vector mesons (i.e. A_1 Regge trajectory for the non-singlet case etc.). It is expected that those Regge trajectories should have relatively low values of their intercepts (i.e. $\alpha_A(0) \leq 0$). This behaviour is however unstable against the QCD evolution which generates steeper x dependence:

$$g_1^{NS}(x, Q^2) \sim exp(c_1\sqrt{\xi(Q^2)ln(1/x)}) \tag{32}$$

$$g_1^{S}(x, Q^2) \sim exp(c_2\sqrt{\xi(Q^2)ln(1/x)}) \tag{33}$$

where

$$\xi(Q^2) = \int^{Q^2} \frac{dq^2}{q^2} \frac{\alpha_s(q^2)}{\pi} \tag{34}$$

and where $c_1 < c_2$ because of the $gg \to q\bar{q}$ mixing in the QCD evolution of polarized singlet densities. Several contributions to the conference discussed specific models for polarized parton denssities with QCD evolution included [44, 47].

Besides the topics summarized above several contributions discussed various issues of multiparticle production in hadronic collissions [49, 48, 50], various QCD tests including the review on fragmentation functions [46] etc. One should finally mention an interesting presentation by Elena Papageorgiou on the the signals of new phase of QED in elastic scattering on nuclei [51].

To sum up we have witnessed enormous progress in both phenomenological as well as the theoretical understanding of the pomeron. Change of its nature with relevant scales is evidently visible in the data and needs satisfactory dynamical explanation.

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